A 3D Numerical Model of Ice Island Calving Due to Buoyancy-driven Flexure

Mahmud Sazidy¹,², Greg Crocker¹ and Derek Mueller¹
¹ Water and Ice Research Lab, Department of Geography and Environmental Studies, Carleton University, Ottawa, ON, Canada
² Defence Research and Development Canada-Atlantic, Dartmouth, NS, Canada

ABSTRACT

Ice islands are extensive tabular icebergs that calve from Arctic ice shelves and floating glacier tongues. As they drift south, they deteriorate by melting and edge-wasting, but they can also fracture, which results in the calving of large fragments from the parent ice island. Fracture events may be related to several factors; however, the buoyancy force associated with underwater rams can yield enough bending stress to cause ice failure. We tested this hypothesis by developing a 3D numerical model using finite element analysis (FEA) model. The model is based on classical theory of solid mechanics and calculates stress across the free-floating ice island as it is subjected to gravitational and buoyancy forces. The model was successfully validated against analytical solutions of a semi-infinite beam-on-elastic foundation theory and an idealized simple beam model. An element erosion technique with a strength-based failure criterion (500 kPa) was employed to simulate fracture initiation and propagation. The results indicate that the buoyancy force from the underwater ram can break the ice island in flexure when the maximum principal stress exceeds the failure criterion. We assessed fracture behaviour of three ice island fragments or icebergs with known geometries. We aim to incorporate our FEA into a comprehensive ice island deterioration model that considers melting, and edge-wasting processes. This model can then be used for ice hazard management in relation to offshore infrastructure and shipping.

KEY WORDS: Ice island calving; Underwater ram; Deterioration mechanisms; Element erosion method; Petermann Glacier

INTRODUCTION

Calving plays a significant role on the deterioration and drift of large icebergs and ice islands. It produces smaller icebergs, bergy bits and growlers which may pose serious risks to ships and offshore infrastructure. Ice islands and icebergs transport a large amount of freshwater far
from their origin, and upon calving and deterioration this freshwater will affect the physical, chemical and biological nature of the surrounding ocean waters (Crawford et al., 2016, Wagner et al., 2014, Crawford et al., 2018). Therefore, it is of interest to understand the physical processes and mechanisms involved with these calving and deterioration processes.

Analyses have been carried out in the past aimed at understanding the calving and deterioration processes of icebergs and ice islands. Most deterioration studies consider surface melting, wave erosion and localized calving loss at the waterline notch (Savage, 2001). These are the processes responsible for most of the deterioration that icebergs undergo. However, for extensive, flat ice islands, it is recognized that a calving event or large-scale fracture due to the formation of an underwater ram plays an important role in their deterioration rate (Wagner et al., 2014). To date, there are only a few models that attempt to capture this large-scale fracture process (Diemand et al., 1987, Wagner et al., 2014). The aim of this study is to develop a numerical tool that improves our understanding of calving or large-scale fracture due to the formation of underwater rams.

Calving or large scale fracture of icebergs and ice islands has been studied analytically and numerically by many researchers (Benn et al., 2007, Crawford et al., 2016, Diemand et al., 1987, Wagner et al., 2014). Diemand et al. (1987) were the first to study the calving of two icebergs observed in Baffin Bay and along the Labrador coast. The study idealized the observed icebergs as a simple beam and a circular plate, and provided analytical solutions to simulate large scale fracture due to underwater rams. The analytical solutions indicated that the underwater rams result in sufficient stresses at the center of icebergs to cause flexural failure. Wagner et al. (2014) also analyzed and modelled the problem in two dimensions (2D) using a beam-on-elastic foundation theory, and investigated the effect of underwater rams on the calving process. These idealized 2D analytical models are useful, but there are characteristics of the problem that are inherently three dimensional (3D), and the best approach to investigate this 3D process is through numerical modelling.

Finite Element Method (FEM) is the most popular and widely used numerical tool to simulate fracture related physical processes. In FEM platforms, the fracture is treated with different integration schemes or methods such as Element Erosion Method (EEM), Cohesive Zone Method (CZM), Extended Finite Element Method (XFEM), Smooth Particle Hydrodynamics (SPH), Discrete Element Method (DEM) etc (Sazidy, 2015). Fundamental theories behind these methods are fracture mechanics, damage mechanics, breaking mechanics and classical solid mechanics. Lu et al. (2012) and Daiyan and Sand (2011) examined several numerical methods such as EEM, CZM, XFEM and DEM for the purpose of simulating flexural failure in sea ice beams against conical offshore structures. Model results indicated that all these methods are capable of simulating flexure-driven fracture. However, EEM is optimal from the perspective of accuracy, modelling effort and computational efficiency (Lu et al., 2012). The EEM is based on a simple solid mechanics theory, and requires a stress or strain-based failure criterion to achieve flexure-driven fracture. In EEM, when a particular element reaches the failure criterion (stress or strain), the element is deleted and initiates the fracture or crack. The EEM has been successfully utilized in Sazidy (2015), Sazidy et al. (2014a) and Sazidy et al. (2014b) to simulate flexural failure of level sea ice against ships.

In this study, a 3D finite element model was developed using the commercial software package LS DYNA to study buoyancy-driven calving (flexural failure) of ice islands. Due to the lack of sufficient field data, the model was validated with analytical solutions of a simple beam-on-elastic foundation, and using an idealized simple beam provided by Diemand et al. (1987). Then the validated numerical model was utilized to assess the stress distributions in three ice island fragments with known geometries. Finally, the EEM was employed to observe fracture initiation and propagation due to the underwater ram.
The overall deterioration process of a glacial ice feature can be categorized into melting and calving. Solar radiation, buoyant vertical convection, forced convection due to ocean current, wave and wind melting, and wave erosion around the waterline are the principal mechanisms that contribute to the melting deterioration process (Savage, 2001). Melting is particularly important for the smaller icebergs, and not a significant contributor to deterioration in sea waters at or below 0°C (Diemand et al., 1987). Calving, on the other hand, plays a key role in the deterioration process of large tabular icebergs which are also known as ice islands. Calving mainly occurs due the stress from ocean swell, self-weight of overhanging beams and buoyancy from underwater rams. Buoyancy-driven calving due to underwater ram is a principal mechanism for large scale mass loss or deterioration in ice islands as identified in Diemand et al. (1987) and Wagner et al. (2014). However, this buoyancy-driven deterioration mechanism has received relatively little attention.

An ideal rectangular shaped ice island (Figure 1a) would float on the ocean water and maintain equilibrium under gravitational and hydrostatic loading. When ice is removed from the ice island sail through localized calving or melting, it results in shape irregularities and underwater rams (Figure 1b). This provides an upward buoyancy stress whose magnitude highly depends on the geometry of the ram. When the upward buoyancy stress magnitude exceeds the flexural limit of the ice island, large scale fracture occurs at the location of maximum stress. Therefore, a large ice island with an underwater ram can be idealized as semi-infinite beam on elastic foundation and subjected to an upward buoyancy load.

![Diagram](image)

Figure 1. An idealized semi-infinite beam on elastic foundation (a) and typical ice island profile with an underwater ram (b)

The upward buoyancy load can be derived from the ram length ($l_r$) and keel draft ($h_k$) as,

$$P_1 = l_r h_k (\rho_w - \rho_i) g [N/m]$$  \hspace{1cm} (1)

where, $\rho_i$, $\rho_w$ and $g$ are the ice density, water density and acceleration due to gravity, respectively. The maximum bending or flexural stress due to the upward buoyancy load of Eq. (1) can be calculated from (Watts, 2001),

$$\sigma_{\text{max}} = 0.644 \frac{E}{(1 - \nu^2)} \frac{P_1 \beta^3 h}{P_w g} [Pa]$$  \hspace{1cm} (2)

The location of the maximum stress in the beam is,
\[ X_{max} = \frac{\pi}{4\beta} [m] \]  

In Eq. (2) and Eq. (3), \( E \) and \( \vartheta \) are the Young Modulus, Poisson ratio, respectively. The parameter \( \beta \) can be estimated from,

\[
\beta = \left[ \frac{\rho_w g}{4} \cdot \frac{12(1-\vartheta^2)}{E h^3} \right]^{1/4} [m^{-1}] 
\]

Diemand et al. (1987) provided simple beam model of iceberg FRANCES that can be used to analyze the stresses across a finite iceberg or ice island with a symmetric underwater ram. Figure 2 shows the idealized beam model of iceberg FRANCES.

The maximum principal stress due to the symmetric underwater ram occurs at the centre of the iceberg, and can be calculated from half the length of the sail \( l_1 \), the length of the ram \( l_2 \), the height of the sail \( h_1 \) and the draft of the keel \( h_2 \) using Eq. (5)

\[
\sigma = \frac{3l_2(l_1 + l_2)}{(h_1 + h_2)^2} h_2 g(\rho_w - \rho_b) [Pa] 
\]

**NUMERICAL MODELS**

Two numerical models were developed to select appropriate physical and mechanical properties of ice islands so that these properties can be used in further fracture assessment of observed ice islands. One is a semi-infinite beam on elastic foundation with an underwater ram at one end. The other one is the finite beam on elastic foundation with symmetric underwater ram at both ends. In both cases, an initial undamped simulation was performed to derive a global damping coefficient for the final numerical models.

The semi-infinite beam model consists of an ice beam that is free-floating on the ocean. The parameters of the model are listed in Table 1. The ice island or the semi-infinite beam was discretized into 4482 solid elements having an approximate element size of 10x8.3x10 m. Model computations and parameterization in LS DYNA are provided as a series of 'cards'.
The MAT_ELASTIC card (a typical material characterization in the LS DYNA material library) was used to define the elastic material behaviour of the ice beam. This material card requires ice density, Young Modulus and Poisson ratio as inputs.

Table 1. Principal particulars of semi-infinite beam on elastic foundation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Length, L</td>
<td>1500</td>
<td>m</td>
</tr>
<tr>
<td>Ram Length, l_1</td>
<td>30</td>
<td>m</td>
</tr>
<tr>
<td>Keel height, h_k</td>
<td>40</td>
<td>m</td>
</tr>
<tr>
<td>Sail/freeboard, h_s</td>
<td>10</td>
<td>m</td>
</tr>
<tr>
<td>Total height, h</td>
<td>50</td>
<td>m</td>
</tr>
<tr>
<td>Width, w</td>
<td>50</td>
<td>m</td>
</tr>
<tr>
<td>Ice density, ρ_i</td>
<td>900</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Young Modulus, E</td>
<td>9.0</td>
<td>GPa</td>
</tr>
<tr>
<td>Poisson ratio, ν</td>
<td>0.33</td>
<td>-</td>
</tr>
<tr>
<td>Water density, ρ_w</td>
<td>1024</td>
<td>kg/m³</td>
</tr>
</tbody>
</table>

The ice island was subjected to two load types - gravity load as a body force and hydrostatic pressure at the bottom surface of the beam. The gravity load was defined with gravitational acceleration vs time curve and applied through the card LOAD_BODY_Z. The hydrostatic pressure, on the other hand, was defined over time with a user defined function on the basis of the standard hydrostatic pressure equation. The pressure curve was applied at the bottom of the beam through LOAD_SEGMENT_SET card (this allows application of a load on multiple element surfaces). Figure 3 illustrates the basis of the hydrostatic pressure (P_{hs}) estimation as a function of water depth (h_w) from a particular reference point and the vertical distance (y_i) of the bottom surface of the beam from the same reference point.

![Figure 3. Hydrostatic pressure at the bottom of the ice beam](image)

The ice island is assumed to be free floating, and therefore boundary and contact definitions are not required for this model. The time step scale factor is set to 0.6 for improved accuracy (this is a scale factor, the actual time step is automatically calculated by LS DYNA based on minimum element size), and the simulation is allowed to run for 100 s. The final semi-infinite beam model is shown in Figure 4.
The maximum principal stress history of an element in the higher stress region (at the bottom of the beam) is shown in Figure 5a. This time series indicates significant fluctuation and numerical instability which is due to the dynamic nature of the system. An appropriate damping coefficient value for the principal stress is required to resolve this problem. The following equation can be used to estimate an approximation damping coefficient ($D_s$) value (Sturt, 2018),

$$D_s = \frac{4\pi}{T}$$

where, $T$ is the time difference between the two consecutive peaks in the maximum principal stress vs time curve. In this semi-infinite beam model, $T$ is 2.16 s based on two clearly visible peaks which gives a value of 5.8 for the damping coefficient. This damping value was inserted into the final model through the DAMPING_GLOBAL card. Figure 5b indicates the time history of maximum principal stress after damping analysis.

A similar modelling approach was followed for the finite beam on elastic foundation model. Identical material properties, section properties and loading curves were used, and only the geometry of the beam differed. The beam consisted of two symmetric underwater rams at both ends. The geometric dimensions were chosen from the idealized model of the
FRANCES iceberg as shown in Figure 2. A time difference $T = 0.68 \text{ s}$ was calculated from the undamped simulation, and the damping coefficient was 18.5. Further discussions on the results are carried out in the following sections.

MODEL VALIDATION

Due to the lack of sufficient field data, the numerical models were validated against analytical solutions of semi-infinite beam and finite beam models. The maximum principal stress and its location are the two primary variables that describe fracture behaviour and the resultant calving event. The magnitude and location of the maximum principal stress are buoyancy-driven, and hence influenced by the size and geometry of the underwater ram. For the semi-infinite beam model, the underwater ram produced the equivalent of an upward buoyancy force of 73 MN. This caused stress to build up at the bottom of the beam near the ram as shown in Figure 6.

The maximum principal stress (Pa) distribution on semi-infinite beam

![Figure 6. Maximum principal stress (Pa) distribution on semi-infinite beam](image)

The magnitude and location of maximum principal stress from the semi-infinite beam model are comparable to the analytical solutions from Eq. (2) and Eq. (3) as shown in Table 2. The location of the maximum principal stress in numerical model is measured from the edge of the sail at the ram end of the beam.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Numerical</th>
<th>Analytical</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Stress Location, $L_{\text{max}}$</td>
<td>331</td>
<td>355</td>
<td>m</td>
</tr>
<tr>
<td>Max Principal Stress, $\sigma_1$</td>
<td>530</td>
<td>511</td>
<td>kPa</td>
</tr>
</tbody>
</table>

The finite beam model results were then compared with the analytical solutions of idealized simple beam (FRANCES) icebergs. Figure 7 is the principal stress distribution on the finite beam, FRANCES. The FEA model predicts that the maximum principal stress would concentrate at the center of the iceberg due to its symmetric ram at both ends. The maximum stress reached up to 0.87 MPa when no fracture was allowed. These numerical results are aligned with analytical simple beam model results (maximum stress value of 0.8 MPa), and an observed fracture event in Diemand et al. (1987) in which the iceberg was split in half.
ASSESSMENT OF FIELD-OBSERVED ICE ISLAND FRAGMENTS

The validated numerical approach and simulation parameters were used to evaluate stress distribution in recently observed ice islands with known geometries. Three observed ice island profiles were considered in this study, they are referred to as: Berghaus, Peterman Ice Island B (PII-B) and the St. Lewis iceberg. Berghaus and PII-B are fragments of Peterman Ice Island in Lancaster Sound and Baffin Bay. Details of these ice island fragments can be found in (Crawford et al., 2018, Crawford et al., 2016, Forrest et al., 2012, Hamilton et al., 2013). The St. Lewis iceberg is named after its observed location. An aerial video of this iceberg was captured near St. Lewis (“Iceberg Alley”), Labrador (Danger Industries, 2015). The video clearly demonstrates the fracture and uplifting of its underwater ram due to the force of buoyancy.

Geometric models of the three ice island profiles were created from field observations of sail height and keel depth and video or still imagery in Hamilton et al. (2013), Li (2013), Crawford et al. (2016), Wagner et al. (2014) and Danger Industries (2015). Geometric shapes and principal dimensions of these ice island profiles are graphically presented in Figure 8. Figure 9 to Figure 11 show the maximum principal stress distribution of the icebergs. The magnitudes and locations of the maximum principal stress describe the fracture behaviour. If the stress magnitude exceeds the flexural strength of the ice island, a flexure-driven fracture will occur.
APPLICATION OF ELEMENT EROSION METHOD

The element erosion method (EEM) was employed to simulate fracture initiation and propagation in the semi-infinite beam and finite beam models. In this method, a critical threshold in stress, strain, mean pressure etc. must be defined to initiate a fracture. When a particular element exceeds that threshold, the element is deleted and initiates the fracture. In this study, a strength-based failure criterion was assigned through MAT_ADD_EROSION in
LS DYNA. Figure 12 and Figure 13 show the stress distribution that is associated with fracture initiation and propagation at different simulation times for a critical stress value of 500 kPa. The upper left images in these figures show stress immediately prior to fracture and subsequent images show stress relief immediately after erosion of elements. The stress quickly builds to the critical value above the eroded notch prior to the next erosion event (not shown). The critical stress value is a reasonable representation of the flexural strength of glacial ice (Wagner et al., 2014). The model correctly predicted the location of fracture for iceberg FRANCES, PII-B and the St. Lewis iceberg (Danger Industries, 2015, Diemand et al., 1987, Wagner et al., 2014). For Berghaus, the failure criterion was never exceeded and no fracture event was modeled. This result is reasonable given that Berghaus did not fracture for several weeks following field observations (Li, 2013).

Figure 12. Maximum principal stress (Pa) distribution indicating fracture initiation and propagation in the semi-infinite beam model

Figure 13. Maximum principal stress (Pa) distribution indicating fracture initiation and propagation in finite beam model (FRANCES)
CONCLUSIONS

A numerical model was developed to investigate flexure-driven calving events in ice islands due to the buoyancy force from underwater rams. The model is based on classical solid mechanics theory, standard hydrostatic formulation, and included strength-based failure criterion. These help to avoid the traditional approach of damage mechanics, fracture mechanics and complicated hydrodynamics, and results a computationally efficient and user-friendly fracture prediction tool. The model was evaluated using observations from three different ice islands and in all cases correctly reproduced the observed behavior (two that fractured and one that did not). The model is designed to be used in a comprehensive ice island deterioration model that considers melting, and edge-wasting processes. Further study should aim to explore the effect of sail and keel geometries, and mechanical properties of ice islands such as Young’s Modulus and flexural strength on the calving process.

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